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Analysis of Renewable Energy Potential in the Residential Sector Through High-Resolution Building-Energy Simulation

INTRODUCTION AND OBJECTIVE

The Canadian residential sector consumes 16 per cent of Canada's total secondary energy, resulting in about 70 megatonnes[1] (Mt) of greenhouse gases (GHG) being released a year. Between 1990 and 2004, overall energy consumption has increased by around 23 per cent, creating an increase in GHG emissions of 24 per cent in all sectors.

One of the strategies to reduce fossil fuel consumption and the resulting GHG emissions is to increase the use of renewable energy.

More than 80 per cent of total residential energy use is for space heating and domestic hot water heating. Technological advances in low-grade residential heat sources and distribution systems, coupled with distributed renewable energy generation, are an opportunity for overall end-use energy savings. However, research is needed on assessing the technical and environmental suitability of such systems to take advantage of these technologies.

The overall objective of this study is to provide technical assessment of the potential of renewable energy systems in low-rise housing.

The first part of the project assesses the feasibility of adding a hybrid, renewable-energy system of roof-mounted, solar photovoltaic (PV) panels and a micro-wind turbine to existing housing.

The second part proposes, models and analyzes an energy-efficient, renewable energy-based heating, ventilating and air-conditioning (HVAC) and domestic hot water (DHW) heating system for new houses.

METHODOLOGY

Integration of PV and Micro-wind Turbine into Existing Housing

This study investigated the economic and environmental impacts of a roof-mounted PV and micro-wind turbine energy system. The study considered 600W and 1000W micro-wind turbine generators.

PV system sizes were dictated by the size and orientation of the roofs of representative houses in different regions. Those sizes were determined based on the statistics conducted on the available databases and only roof surfaces facing east, south, and west were considered for PVs.

To choose representative test-case houses, the researchers analyzed data from three of Canada's most comprehensive housing stock and residential end-use energy databases:

1. The *Survey of Household Energy Use* (SHEU) database (Statistics Canada, 1993)[2].
2. The *EnerGuide for Houses* database (EGH) (NRCan, 2005).
3. The *New Housing Survey* database (NHS) (NRCan, 1997).

Fifty-seven test-case houses were selected based on province, age and space-heating fuel type. Construction and thermal characteristic and attributes of the typical test-case houses were determined by analyzing the data in the databases. To account for the effect of electrical appliance usage on the house electrical and thermal loads, 15-minute, interval-based electricity-load profiles were estimated for each test-case house. The selected test-case houses represented 62 per cent of the total housing stock according to the 1993 SHEU database.

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1 A megatonne is one million tonnes. Greenhouse gas emissions are usually measured in megatonnes.

2 Three SHEU databases are available, 1993, 1997, and 2003. The 1993 one is by far the most comprehensive SHEU database. Moreover, a complete set of raw data, including the fuel bills and appliance Make and Model information for a subset of houses, is available from the 1993 SHEU while only limited data is available to the public from the 2003 SHEU.

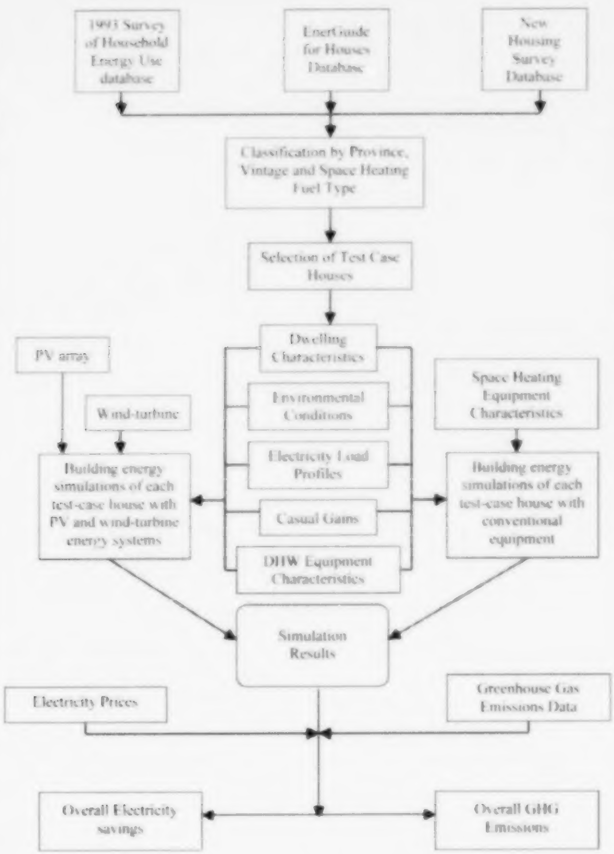

Figure 1 Flowchart of the methodology for the study of existing housing stock

The test-case houses were then simulated in ESP-r (Environmental Systems Performance; r for "research"), open-source building and plant energy and environmental simulation software. Two sets of simulations estimated the thermal and electrical energy needs of the test-case houses.

1. The base-case simulations used existing space heating and DHW equipment with electricity from the grid. Annual simulations estimated the space heating, domestic hot water heating and electricity demand of the test-case houses. Total GHG emissions due to thermal and electrical energy use were estimated along with the cost of electricity at flat and the proposed time-of-use (TOU) rates.
2. The hybrid-case simulations used existing space heating and DHW equipment, but with PV and wind turbine as alternate energy sources. Annual simulations estimated the renewable energy produced by the PV and wind turbine. The reduction in GHG emissions from electricity contributed by this system to the house electrical demand was estimated. The cost of annual electricity consumption was estimated at flat and proposed TOU prices. The credit for selling surplus electricity to the local grid was also estimated.

The two cases were compared and the results extrapolated at the national level to assess the potential GHG reductions from integrating the roof-mounted PV and micro wind turbine system. Figure 1 is a flowchart displaying the methodology used to study existing housing stock.

Renewable-energy-based HVAC and DHW for New Housing

An energy-efficient, renewable-energy-based HVAC and DHW heating system for new construction housing was proposed and modelled to assess its end-use energy savings potential and emission performance. Since only a small percentage (approximately one per cent [NRCan, 2003a]) of residential end-use energy consumption was attributed to cooling in Canada, this work concentrated on space heating, DHW and occupant-driven electricity consumption.

The proposed residential heating system had two main components.

1. A hybrid HVAC system that transported heat from the ground in the heating season and distributed this thermal energy throughout the residence.
2. A hybrid renewable electricity system that provided the electricity required to run the HVAC system from photovoltaic electricity generation enhanced by storage and control schemes. The hybrid HVAC system provided both heating and ventilation to the residence.

The proposed system consisted of a ground heat exchanger (GHX), ground source heat pump (GSHP), in-floor radiant heating and a heat recovery ventilation (HRV) system. In particular, the system included a GHX that utilized the near-constant, year-round temperatures of the earth (about 4 to 12∞C [39 to 53°F]), which was upgraded by a heat pump.

The heat pump provided conditioned water (about 35 to 40¤C [95 to 104°F]) to two separate HVAC systems:

1. A radiant in-floor loop to provide sensible heating to the conditioned residential zones.
2. A DHW loop preheated with excess thermal energy when available from the GSHP system.

An HRV system was incorporated to minimize the heating load necessitated with conditioning outdoor air directly. A hybrid system of renewable electricity generation met the electrical demands of the residences and the separate systems. Photovoltaic modules in conjunction with electricity storage provided by the grid in a net metering arrangement balanced the variable nature of renewable electricity generation. Figure 2 is a schematic of the proposed hybrid system.

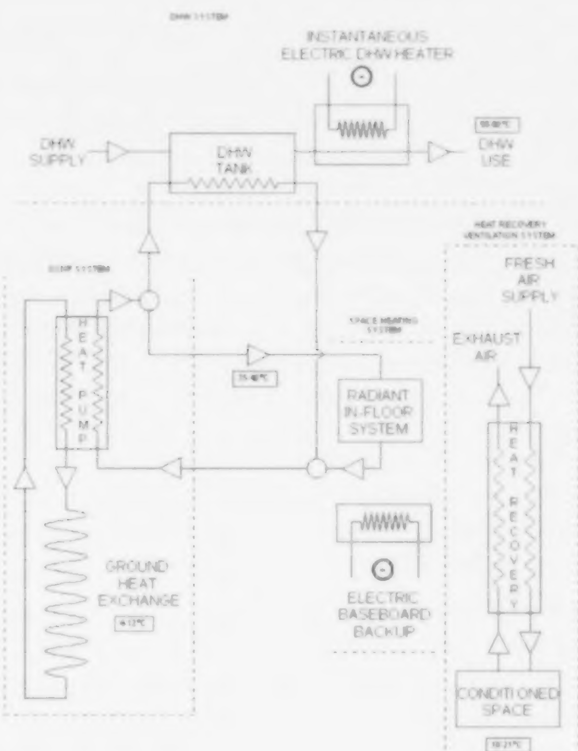

Figure 2 Schematic of the hybrid HVAC system

A base model was needed for the study that depicted a common, single-family dwelling for use in determining energy performance in four climatic regions across Canada. The researchers chose the Canadian Center for Housing Technology (CCHT)[3] test house in Ottawa, as it accurately represents a typical new energy-efficient R-2000 house and was already modelled within ESP-r (Purdy & Beausoleil-Morrison, 2001a). Since Ottawa is the actual location of the CCHT test house, it served as the original location for all simulations during the model's development.

Energy simulations were then conducted in ESP-r for this common R-2000 Canadian home with different parameters.

In the "base-case," simulations were conducted for sample climatic regions—Pacific, Prairies, Central and Atlantic, represented by Vancouver, Calgary, Ottawa and Halifax, with each region's heating fuel and equipment type.

In addition, a simplified, in-floor heating model was developed in ESP-r to assess the dynamic behaviour of the in-floor radiant heating system. A sensitivity analysis was conducted on the in-floor heating model to assess the energy saving potentials and the associated emissionreductions.

In the hybrid-case, simulations analyzed the energy performance and environmental impact of the proposed HVAC system by varying system configurations as well as the size of the heat pumps, supply system, thermal storage, electrical storage and photovoltaic components. This analysis determined whether this hybrid system was technically feasible for the Canadian residential market.

The end-use energy consumption of the proposed hybrid energy system and the commonly used conventional HVAC and DHW systems in the four climatic regions were compared.

The end-use energy consumption results determined the net GHG emissions for each hybrid energy system scenario. They were compared with the emissions produced by the conventional HVAC and DHW systems in the four climatic regions.

3 CCHT is jointly operated by the National Research Council, Natural Resources Canada, and Canada Mortgage and Housing Corporation. This research and demonstration facility features two highly instrumented, identical R-2000 homes with simulated occupancy to evaluate the whole-house performance of new technologies in side-by-side testing. For more information about the CCHT facilities please visit http://www.ccht-cctr.gc.ca

RESULTS AND CONCLUSIONS

Integration of PV and Micro-wind Turbine into Existing Housing

Figure 3 shows the average electricity generation potentials in kWh/year with the integration of the PV and micro-wind turbine energy system in the test-case houses. Total electricity generation potentials vary greatly from province to province, with the lowest in Newfoundland and the highest in Alberta. However, in Newfoundland the electricity generation potential from wind was the highest and from PV the lowest. This can mainly be attributed to the province's windy and foggy climate.

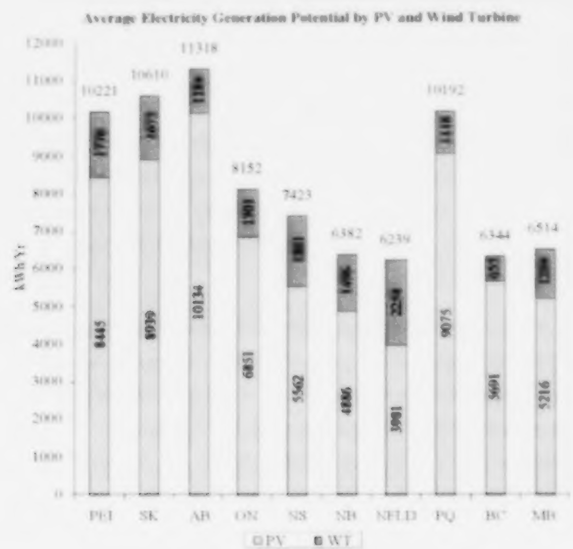

Figure 3 Average annual electricity generation potential using the combination of PV and wind turbine energy system for test-case houses

The stack graph shows the average annual electricity generated by each of the renewable technologies for these houses in a given province. The sum of the renewable electricity generated by the PV and the wind turbine is presented on top of stack bar for each province.

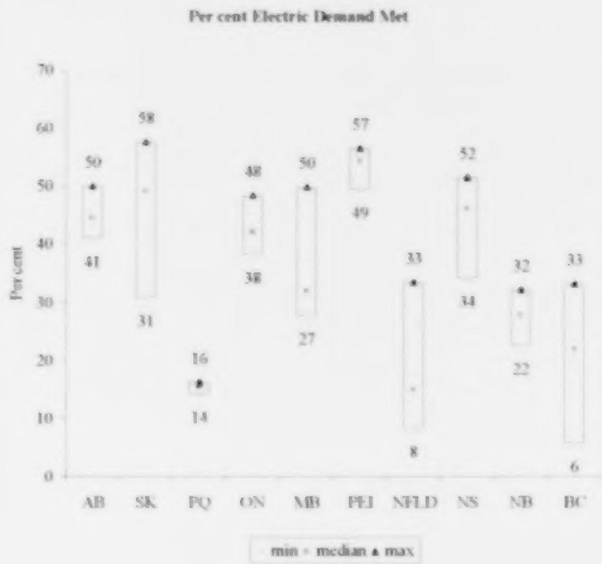

Figure 4 Percentage of electricity demand met by the PV and wind-turbine energy system on time

Figure 4 shows the range of the percentage of electricity demand met on time by the PV and wind-turbine energy system (not including the surplus electricity produced due to mismatch between the occurrence of electricity demand and production of renewable electricity by this system). In Alberta, up to 50 per cent and in Saskatchewan, up to 58 per cent of electricity demand could be met by the hybrid system. However, in Quebec, this was only up to 16 per cent, as the amount of electricity demand that could be met by the electricity generated by the hybrid systems represents a smaller percentage of the total electricity demand in Quebec in comparison with other provinces where more space heating and DHW is provided by non electricity sources.

For selected test-case houses in Ontario and Manitoba, up to 50 per cent of electricity demand could be met on time using hybrid energy systems, showing significant potential of these technologies in terms of meeting electricity demand. In Prince Edward Island, up to 57 per cent and in Nova Scotia, up to 52 per cent of electricity demand could be met with such systems. In New Brunswick, Newfoundland and British Columbia, a demand for electricity of up to 32, 33 and 33 per cent, respectively, could be met.

The percentage of electricity demands met by the PV and wind-turbine energy system for the test-case houses was strongly dependent on a few factors apart from the available potential of PV or wind energies in a given location. For example, in houses with the space and DHW heating systems run by electricity, there was considerable increase in the annual electricity demand. Similarly, higher appliance and lighting electric loads could lower the percentage of electricity demand met by the use of PV and wind turbine.

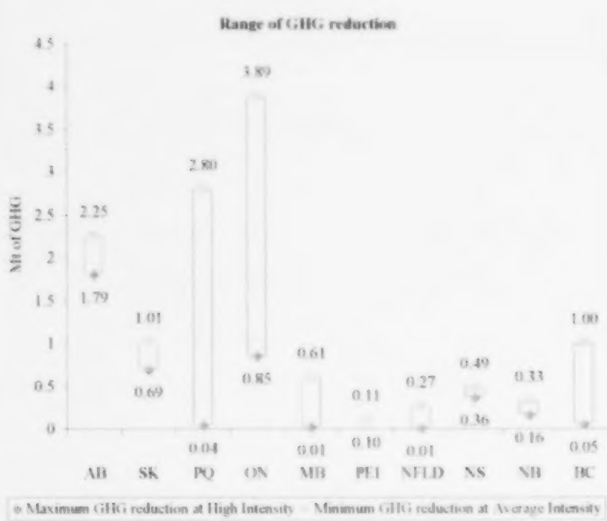

Figure 5 GHG reduction potential at average and high intensity emission factors for all provinces

Figure 5 shows the range of GHG reduction potentials at the provincial level using PV and micro-wind turbine. The ranges of GHG reduction are presented between configuration 1 (PV and 600W wind turbine) at average GHG emission intensities and configuration 2 (PV and 1kW wind-turbine) at high intensities for all provinces.

The lower limit gave the minimum quantity of GHG emissions displaced while the higher limit showed the maximum quantity of GHG displaced. The actual reduction was between these two extremes.

An important factor dictating the potential for GHG reduction of employing these renewable technologies is the provincial electricity-emission-intensity factor. The magnitudes of these factors varied considerably.

For example, the average intensity factors were low in Quebec (8 gCO_2 eq/kWh), Newfoundland (21 gCO_2 eq/kWh), Manitoba (31 gCO_2 eq/kWh) and British Columbia (24 gCO_2 eq/kWh). As a result, the use of such technologies did not result in significant reductions in GHG because of their already lower contribution to GHG emissions due to electricity generation. However, the provinces with higher average electricity-related GHG emission factors showed higher reduction in GHG emissions. It should be noted that both average and high provincial electricity GHG-emission factors were used in the analyses. Average emission factors were based on the overall provincial electricity generation mix. High emission factors were based on the fossil fuel fired generation mix.

Moreover, it was found that the proposed, integrated, renewable-electricity system could only offset a portion of the existing household electricity demand. However, the use of PV and wind-turbine technologies resulted in direct reduction of electricity bills. Excess electricity could be sold to the local grid for which the house owner could earn credit. It was found that for most of the test-case houses, the credit of selling surplus electricity to the grid could significantly contribute to the reduction of net electricity cost.

The results were extrapolated to the national level to assess the potentials of GHG reduction using this system. Table 1 gives the GHG emission reduction potential at the national level. Using these technologies could result in annual GHG reductions of 4.4 Mt, based on average GHG intensities, and 12.7 Mt based on high GHG intensities of electricity generation. These GHG emission reductions would correspond to 15 per cent and 20 per cent of the base case emission levels without the proposed integrated renewable electricity generation system.

Renewable-energy-based HVAC and DHW for New Housing

The findings concluded that the use of the proposed HVAC and DHW system resulted in significant end-use energy savings for all four Canadian climatic regions. The HVAC-related end-use energy savings varied from 47 to 53 per cent when compared with the base case.

Adding PV electricity generation to the proposed system resulted in an even greater annual end-use energy savings, in the range of 56 to 62 per cent. However, the analysis showed that the energy and environmental benefits of the proposed hybrid heating system in a typical R-2000 house varied from region to region, mainly as a result of the difference in climatic conditions and fuel type availabilities.

Sensitivity analysis found that, without including the primary heating system, the in-floor heating system would use 10 per cent more energy for space heating than a conventional forced air system with the same dry-bulb temperature set point. The reason for the difference is the high thermal mass and slow response.

However, there was considerable spacing heating energy savings —11 per cent—for the in-floor heating system if operative temperatures (termed "reduced" here) were maintained instead of dry-bulb temperatures.

Table 2 compares space-heating energy demands in a typical Ottawa winter week for the forced air system and in-floor heating system. Figure 6 shows the dry-bulb temperature profiles for an ideal thermostat control, forced-air system and for an in-floor radiant heating system.

Tables 3 and 4 are some of the results showing the effectiveness of implementing the proposed HVAC system when compared to the base case of Ottawa. Table 3 shows the end-use energy savings and Table 4 the GHG reduction potential that could be achieved. Table 5 compares the energy savings and Table 6 the GHG reduction potentials of the proposed system for all four cities.

The proposed HVAC system resulted in simulated end-use energy savings when compared with the base case in the order of 50 per cent for all four of the simulated Canadian climatic regions.

The analysis also found that for regions with an electricity generation mix with a low GHG-emission factor, incorporating an advanced building HVAC system played an important role in further reducing harmful GHG emissions. For regions with an electricity generation mix that relied heavily on fossil-fuel combustion, although the proposed HVAC system still reduced end-use energy consumption by half, the emphasis should be placed on small-scale, distributed renewable energy generation (such as photovoltaics) to reduce the GHG emissions contributed by the residential sector.

Other findings showed that:

- a night setback control strategy could be one way of saving energy with in-floor radiant heating system;
- the proposed DHW preheating scenario resulted in significant end-use energy savings, reducing the DHW load by 42 per cent when compared with a common fuel-fired tank system;
- the use of a net metering scheme made using PV- generated electricity practical as the grid was used as electrical storage.

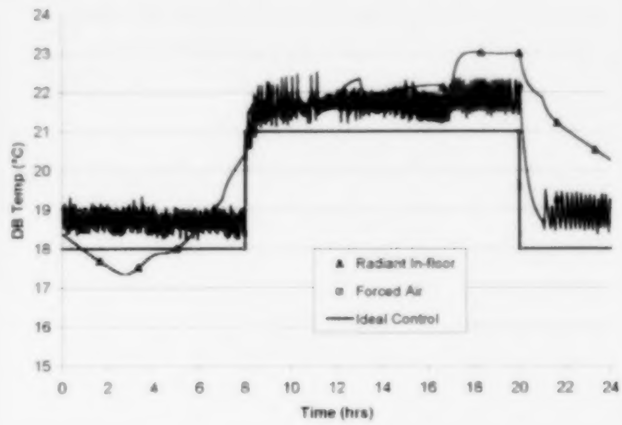

Figure 6 Forced air and radiant temperature profile comparison using a dry-bulb thermometer

The proposed in-floor heating system had a difficult time maintaining the set-point temperature, particularly in the afternoon when solar and internal gains were high, thus leading to overheating.

Table 1 Total annual GHG emission reduction potential at national level

Emission intensity factors	GHG savings with PV and 600 W wind-turbine (Mt)	Per cent saving compared to total base-case GHG emissions	GHG savings with PV and 1 kW wind-turbine (Mt)	Per cent saving compared to total base-case GHG emissions
Average	4.1	14.1	4.4	15.3
High	11.9	19.5	12.7	20.1

Table 2 Comparison of heating end-use energy demands for forced air and radiant systems

HVAC type	Temperature setting	Weekly heating load (MJ)	Compare to base case (% diff)
Forced-air (base case)	Regular	2,950	—
In-floor radiant	Regular	3,230	+9.5
	Reduced	2,620	-11.2

Table 3 End-use energy consumption comparison for the entire building: base case and proposed hybrid HVAC system (Ottawa)

Ottawa Jan. 1–Dec. 31	Base case (GJ)	Proposed (GJ)	
	Regular temperature setting	**Regular temperature setting**	**Reduced temperature setting**
Occupant driven–Electrical	32.18	32.18	32.18
HVAC and DHW–Electrical	4.43	34.16	30.18
HVAC and DHW–Non-electrical	59.77	0	0
PV generation–Electrical	—	- 23.94	- 23.94
Net electrical	**36.61**	**42.40**	**38.42**
Net non-electrical	**59.77**	**0**	**0**
Net energy consumption	**96.38**	**42.40**	**38.42**
Net energy savings	**—**	**56%**	**60.1%**

Table 4 GHG emission comparison for entire building: base case and proposed hybrid HVAC system

Ottawa Jan. 1–Dec. 31	Base case (tonnes CO_2)	Proposed (tonnes CO_2)	
	Regular temperature setting	**Regular temperature setting**	**Reduced temperature setting**
Net electrical emissions	2.81	3.25	2.95
Net non-electrical. emissions	3.38	0	0
Net GHG emissions	6.19	3.25	2.95
Net emission savings	—	47.5%	52.3%

Table 5 End-use energy consumption comparison for the entire building: base case and proposed hybrid HVAC system for all four cities

Jan. 1–Dec. 31	Base case (GJ)	Proposed (GJ)	
	Regular temperature setting	Regular temperature setting	Reduced temperature setting
	Halifax		
Net energy consumption	88.14	39.21	36.40
Net energy savings	—	55.5%	58.7%
	Ottawa		
Net energy consumption	96.38	42.40	38.42
Net energy savings	—	56%	60.1%
	Calgary		
Net energy consumption	96.63	40.76	36.69
Net energy savings	—	57.8%	62%
	Vancouver		
Net energy consumption	79.15	35.08	33.47
Net energy savings	—	55.7%	57.7%

Table 6 Greenhouse gas emission comparison for entire building: base case and proposed hybrid HVAC system for all four cities

Jan. 1–Dec. 31	Base case (tonnes CO_2)	Proposed (tonnes CO_2)	
	Regular temperature setting	Regular temperature setting	Reduced temperature setting
	Halifax		
Net GHG emissions	11.72	8.27	7.67
Net emission savings	—	29.4%	34.6%
	Ottawa		
Net GHG emissions	6.19	3.25	2.95
Net emission savings	—	47.5%	52.3%
	Calgary		
Net GHG emissions	12.41	9.99	8.99
Net emission savings	—	19.5%	27.6%
	Vancouver		
Net GHG emissions	2.78	0.35	0.33
Net emission savings	—	87.4%	88.1%

IMPLICATIONS FOR THE HOUSING INDUSTRY SECTOR

The project demonstrated that there were opportunities for the generation of renewable energy in the residential sector to meet part of the overall energy demand in the sector.

However, the study focused only on solar PV, micro-wind turbine and ground-source heat pump technologies without considering other measures, such as energy-efficiency upgrades and solar thermal systems.

The study concluded that without substantial reduction in the overall energy demand, in both electricity and thermal, in conjunction with the utilization of passive and active solar thermal systems in existing and new housing, the technologies investigated could not meet the energy demand in the residential sector. It recommends that all of these measures should be incorporated and investigated in a holistic way in future studies.

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